Lithostrotion irregulare, Phill.
L. junceum, Flem.
Zaphrentis sp.
Crinoid ossicles (many large).
Echinoid spines and plates.
Batostomella sp.
Rhabdomeson rhombiferum, Phill.
Athyris ambigua, Sow.
Orthis resupinata, Mart.
Productus semireticulatus, Mart., var.
Productus, several species indet.
Productus spines.
Rhynchonella pleurodon, Phill.
Aviculopecten sp.
Nucula gibbosa, Flem.
Nuculana attenuata, Flem.
Bellerophon Urei, Flem.
B. decussatus, Flem.
Loxonema sp.
Macrochilina sp. (*imbricata*?), Sow.
Pleurotomaria sp.
Orthoceras sp.

About this assemblage of fossils there is something that is here peculiar. Suppose I were requested to collect such a suite from the stratified rocks of North-Eastern Fife I should certainly not go to any portion of the Calciferous Sandstones (the strata through which the agglomerate can be seen to rise), but to some of the well-marked marine horizons in the lower portion (Lower Limestones) of the next overlying group of sediments, the Carboniferous Limestones. It would, of course, be natural to expect that the fragments which furnished the foregoing list of fossils must have been derived from some calcareous stratum underlying this precise portion of the coast-line anterior to the volcanic outburst. As has been said, however, the only known limestone at this part is the Encrinite-bed, but from that horizon the following species have not so far been obtained—*Lithostrotion irregulare*, *Zaphrentis*, and *Orthis resupinata*. In addition to this the mode of occurrence of the corals is quite different from that in the Encrinite-bed. Blocks are found entirely made up of the cylindrical corallites of *Lithostrotion*, and are just such as we should expect to have been derived from some of the Lower Limestones. Again, the size of the blocks renders an Encrinite-bed parentage improbable; one at the upper part of the beach was found to measure 20 × 14 × 12 inches, and the Encrinite-bed in the near vicinity is only some 5 inches thick.

Having therefore established the fact that these limestone fragments belong to a higher stratigraphical horizon than any through which the vent can now be seen to rise, how can their presence here be accounted for? The most probable explanation appears to be that some at least of the Lower Limestones formerly overspread this portion of the county, and were actually penetrated by the vent. The disrupted fragments were enclosed in the agglomerate which subsequently subsided within the orifice, while the overlying and surrounding sedimentary rocks have been entirely swept away.

III.—On some British Pillow-lavas and the Rocks associated with them.

By Henry Dewey and John Smith Flett.

(By permission of the Director of H.M. Geological Survey.)

THE pillow-lavas are a group of basic igneous rocks that occur, in our experience, only as submarine flows, and very frequently exhibit 'pillow-structure'. A lava-flow of this type is composed of sack-shaped masses, globular or elongated, and varying in size. The external surface of the pillows may be compact, but in their interior there are numerous cavities often concentrically arranged. First described in Britain by Nicholas Whitley (1), and figured also by De la Beche (2), they have become generally known through the work of Teall (3), Raisin (4), Reid and Dewey (5), and their importance among the Palæozoic eruptive rocks of Britain is now well established.

Although pillow-structure is rarely completely absent, it may not be well exhibited in every exposure of these rocks, especially when, as in Cornwall and Devon, they have been exposed to earth-movements and folding. On the other hand, pillow-structure may make its appearance in rocks that do not strictly belong to this group. Thus it is sometimes seen in the Carboniferous basalts of the Lothians and Fife (6), though not well developed.

The name spilites was given to rocks of this class by Brongniart (7) in 1827, and has recently, in accordance with the usage of Continental petrographers, been adopted by the Geological Survey to designate the Carboniferous, Devonian, and Ordovician pillow-lavas of Devon and Cornwall. It was first used in English by Bonney (8) for certain rocks in Jersey that seem to be properly included in this group.

In addition to the pillow-structure there are certain characteristics that mark the spilites of Great Britain. The first of these is that they are as a rule very completely decomposed, and the second that their felspars are always rich in soda. Their micro-structure varies within rather narrow limits. The principal component is felspar; next in importance is augite of pale-brown colour; remains of olivine are sometimes, though not often, to be detected. Frequently they seem to have contained a fair amount of glassy base, though this is always devitrified and decomposed. Their felspars are occasionally microporphyritic, and often those of the ground-mass have pointed or acicular forms. A few British spilites have large felspar phenocrysts. Sometimes they consist almost wholly of felspar laths with a fluidal arrangement. A large number of spilites are variolitic, and in these the augite may occur as irregular masses enclosing the ends of felspar rods, so that the structure may be described as sub-ophitic.

The advanced decomposition exhibited by the vast majority of these rocks has led to their being classed as 'diabase-porphyrites'; and when they are sheared they form typical 'schalsteins'. We find these characters not only in the pre-Cambrian and Ordovician spilites. In Cornwall the Devonian and Carboniferous spilites and schalsteins never contain olivine or augite, but their ferro-magnesian minerals are completely replaced by secondary products (chlorite, calcite, and epidote).

The felspar is sometimes decomposed beyond identification. Dr. Teall (9) was the first to determine its real nature in the pillow-lavas of the Southern Uplands of Scotland. He recognized it as oligoclase, and confirmed this identification by chemical analyses. We have examined hundreds of sections of spilites from Cornwall and Devon, and have found that the only felspar they contain is albite or albite-oligoclase.

There are two ready tests by which this felspar can be recognized. It has all indices of refraction lower than that of Canada balsam, which in the slides made for the Geological Survey has very closely the refractive index of the ordinary ray of quartz (1·544), and in convergent light it has positive optical sign. These tests exclude all felspars more rich in lime than oligoclase-albite, and are better than any methods depending on extinction angles. The only difficulty in applying them is that the felspar is often filled with minute grains of chlorite and epidote. We shall see that chemical analyses have in several cases placed the identity of the felspar beyond question.

The albite is sometimes very clear and transparent, suspiciously so when we remember the highly decomposed state of the rocks in which it occurs. At other times it has a milky translucency, while in many rocks it is filled with infinitesimal grains of chlorite or epidote. Hence there is reason to believe that in some degree the soda-felspar may be secondary, and that possibly the rocks have been albitized. Now albitization, or the replacement of other felspars by albite, takes place in many ways, as might be expected in a phenomenon so generally displayed by the older igneous rocks. Apparently it is sometimes a result of ordinary processes of weathering by which albite and calcite or epidote replace lime-soda plagioclase. Among the best instances of this type the rocks of Bardon Hill in Charnwood Forest may be adduced. Their felspars were zonal with basic centres, and the interior of the crystals is now a meshwork of albite enclosing many grains of epidote, while the margins are nearly solid albite. Albite and epidote or zoisite may also arise from lime-soda felspar through shearing, as in many of the amphibolites derived by movement from the basic intrusive rocks of the North-East Highlands of Scotland. But albite also replaces lime-soda felspar by a process of albitization, as Bailey and Grabham (10) have shown, which may be a juvenile, post-volcanic, or pneumatolytic mode of alteration.

In the Cornish pillow-lavas the felspars occur in several distinct states. They may be entirely replaced by calcite, quartz, and sericite, as in many lavas of Brentor. In other rocks the lath-shaped sections of felspar are a network of albite with the interstices occupied by secondary minerals such as chlorite and calcite. We can hardly avoid the suspicion that what lime felspar was originally present has been dissolved out, as in the rocks described by Termier (11) and the gaps filled in with decomposition products. But in a fair number of the rocks of this class the albite is clear and fresh, by no means very full of inclusions, and has much of the appearance of a primary mineral. Yet all the other components of these spilites have been completely decomposed; no augite can be found in them, and the matrix is a dense aggregation of secondary products. An example of this class is furnished by the lava of Devonport Workhouse near Plymouth (12). Its albite crystals are not zonal except that their interior is rather spongy and full of secondary inclusions, while their external portions are compact.

In rocks of this type it must be conceded that albitization of soda-lime felspar has occurred on a not inconsiderable scale. We believe that this is to be ascribed to a pneumatolytic change that affected the spilites very shortly after their effusion. It must be remembered these are only the westward prolongation of a great series of pillow-lavas (13) (with attendant keratophyres, minverites, etc.) that extend from Moravia through Nassau across the Rhine into England. Many accounts of these Devonian schalsteins have been furnished by Continental petrographers. Some have noticed their richness in soda, but other felspars are often described as characterizing this group of rocks. Many of them contain fresh augite and labradorite or andesine, in others the felspar is partly oligoclase. The Devonian spilites of the West of England contain no pyroxene and no felspar but albite. Yet there can be no doubt that they are the effusive rocks of one eruptive period, furnishing one of the best examples of a petrographical province that could be adduced. Hence, as the most decomposed rocks contain most albite it seems reasonable to assume that the mineral is in some way of secondary origin.

In these rocks albite occurs sometimes in vesicles and veins, but the minerals of the amygdules are mostly calcite, chlorite, and quartz. The highest lavas of the series are interbedded in the Lower Carboniferous. At the close of the Carboniferous period the Armorican earth-movements began. The spilites were crushed and, when highly vesicular, were torn in shreds. Their felspars are broken and twisted, and the evidence of the slides proves that before the movements set in the albitization and decomposition were complete, for the broken albites are not healed or their fractured surfaces united by new deposit.

Shortly after the movements ceased (perhaps before they were completely at an end) great eruptive granites, of which the Dartmoor mass is the best known, invaded the region. The lavas were at that time rotten and sheared, and their vesicles filled with secondary minerals. Within the aureoles of the granite bosses they were now hornfelsed and their albite felspar replaced by andesine and labradorite, while their calcite and chlorite gave rise to epidote, augite, biotite, and hornblende. The basic felspar can be traced in every stage of development as we follow the spilitic lavas from the outer precincts of the aureoles to the actual contacts with the granite; and that the felspar is recrystallized from a mineral that was full of secondary products can be proved by the abundance in it of specks of hornblende, augite, and biotite, that gradually coalesce to larger grains as the alteration becomes more intense. The new basic felspar produced in this way in late Carboniferous times is still perfectly fresh and clear; this proves that some factor other than mere lapse of time with concomitant weathering must be regarded as the prime agency of albitization in this case.

To show the chemical composition of these rocks we quote some analyses that have been prepared in the laboratory of the Geological Survey. These demonstrate clearly the essential characters of the group: they are basic rocks much decomposed and rich in carbonates and combined water. In all cases the soda is high for basic rocks, while the potash is very low. If the carbonic acid of the first, second, and third analyses is assumed to be combined with lime to form calcite, an assumption that has been verified by chemical tests, the amount of lime felspar present must be quite negligible.

ANALYSES OF BRITISH SPILITES.

	I.	II.	III.	IV.
SiO_2	51·31	46·4	47·56	40·55
TiO_2	1·92	·24	2·40	2·95
Al_2O_3	12·67	20·4	14·27	16·65
Fe_2O_3	·54	6·9	1·63	1·13
FeO	7·99		6·80	9·46
MnO	·45	—	·30	·20
$(CoNi)O$	? trace	—	·08	·07
BaO	nt. fd.	—	nt. fd.	nt. fd.[1]
CaO	8·17	7·7	10·95	6·06
MgO	2·19	3·5	4·90	5·20
K_2O	·54	·54	·27	·27
Na_2O	5·21	6·93	4·61	4·76
Li_2O	? trace	—	? trace	? trace
H_2O (at 105° C.)	·04	—	·42	·27
H_2O (above 105° C.)	2·31	1·1	2·65	3·89
P_2O_5	·90	—	·19	·73
FeS_2	·30	—	·22	—
S	—	—	—	·10
Fe_7S_8	·17	—	·05	—
CO_2	6·15	5·8	2·95	7·85
	100·86	99·51	100·25	100·14

I. West side of Tayvallich Peninsula, Argyllshire (analysed by E. G. Radley, S. 12453).

II. Gatelochside Burn, near New Cumnock, Ayrshire (analysed by J. J. H. Teall). "The Silurian Rocks of Britain"; vol. i, Scotland: Mem. Geol. Surv., 1899, p. 85.

III. Tregedden, South Cornwall (analysed by E. G. Radley, E. 5791).

IV. Devonport Workhouse Quarry (analysed by W. Pollard). "The Geology of the Country around Plymouth and Liskeard": Mem. Geol. Surv., 1907, p. 97.

The Albite-diabases.

With the spilites both in Europe and America, diabases invariably occur, representing the intrusive magma that consolidated below the surface. Some of them contained olivine, but their characteristic minerals are purplish augite (of various shades), plagioclase felspar, and titaniferous iron-ores. Like the spilites they are rarely fresh; their olivine is always decomposed and their augite is frequently replaced by chlorite, epidote, and calcite, though it is far more commonly in good preservation than the pyroxene of the spilites. The only felspar in the vast majority of these rocks is albite, and it is often present in surprising quantity. That basic plagioclase originally formed the inner zones of many felspar crystals may be assumed from the frequency with which the albite has a spongy centre filled with epidote, prehnite, and chlorite, while the margins are compact. But in these diabases veins and segregations occur that are of paler colour and especially rich in soda-felspar, in fact they are almost pure albite rocks. Instances may be cited from Newlyn Quarry, Cornwall (14), and Trusham in Devon, and similar rocks have been described from Germany by Brauns (15). On analysis many of the diabases differ but little from ordinary diabases except in the slightly higher percentage of soda that they contain. Others, however, contain as much as 5 per cent. of soda, an unusual amount for rocks of this type. There can be no doubt that they are a basic group characterized by abundant alkalies and hence possessing affinities with essexite, as has been recognized by Flett (16), Ehrmannsdorfer (17), and Weber (18).

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[1] A substance is reported as not found (nt. fd.) when, though searched for in the usual way, no traces of it have been obtained by the analyst.

It is equally certain that in some cases they have been albitized and have had additional soda-felspar introduced after they had consolidated. An example occurs in the Kit Hill diabase (19). It has large rectangular felspars with interstitial anidiomorphic augite and iron-ores. The two last-named minerals are rather decomposed, but the felspar is very fresh, clear, and homogeneous. It occurs in fairly large crystals which are not zoned, and it has the optical properties of albite. By means of bromoform it was separated from the crushed powder of the rock, and analyses confirmed the optical tests by showing that it was almost chemically pure albite.

In Cornwall and Devon the albite-diabases, like the spilites, were completely decomposed and albitized before the late Carboniferous earth-movements, and were hornfelsed by the granites. Their soda-felspar was then replaced by andesine and labradorite, which is still in excellent preservation. Here again it is certain that the albitization ensued very soon after the rocks were intruded, and we infer that it was of pneumatolytic character.

MINVERITES (PROTEROBASES).

Certain rocks from North and East Cornwall that were described by Teall (20) as hornblendic diabases were subsequently described by Flett (21) as proterobases. In 1910 Dewey (22) proposed the name minverite for similar rocks from St. Minver, North Cornwall. They are much like the diabases, but contain fresh brown primary hornblende. Sometimes traces of olivine (never fresh) occur in them; they are not usually ophitic, and contain much brown and purplish augite. Primary alkali-felspar, mostly albite, is often abundant in the minverites. Analyses of these rocks from Cartuther and St. Mabyn show that they are of the sub-alkalic group of basic rocks, very close in many respects to the essexites. Often they contained a limited amount of lime-soda felspar, now replaced by albite, epidote, and prehnite, or in some cases almost wholly albitized. Other features of this group are the striking abundance of apatite in long thin prisms, and the occasional presence of deep-brown biotite. At Polyphant they are closely associated with the hornblende picrites.

QUARTZ-DIABASES.

Here and there in Cornwall quartz-diabases (23) occur among the spilites and albite-diabases, and belong to the same volcanic epoch. Yet in these rocks the basic felspars remain, every zone is perfectly distinct, the most basic in the interior, the most acid externally. Clearly, then, the albitization is a process intimately connected with the nature of the individual rock; the spilites and quartz-free diabases show it, but the quartz-diabases do not. We are reminded of the manner in which some granites are attended by pneumatolytic phenomena (formation of greisen, etc.) while others are practically free from them. Bailey & Grabham (24) showed that the quartz-diabases of Scotland are occasionally albitized, but only locally and incompletely.

Picrites.

Several picrites have been recorded from Cornwall and Devon, mostly hornblende picrites. Similar rocks occur in the Devonian of the Rhine. They contain a little felspar, usually labradorite or bytownite, and, as in the quartz-diabases, it is not albitized.

ANALYSES OF ALBITE-DIABASES, MINVERITE, AND PICRITE.

	I.	II.	III.	IV.
SiO_2	59·84	46·73	47·19	39·14
TiO_2	·64	2·74	2·09	1·66
Al_2O_3	15·71	18·73	13·96	7·59
Fe_2O_3	1·68	nt. fd.	3·39	5·26
FeO	7·03	10·14	9·01	8·76
MnO	·12	·37	·47	·56
$(CoNi)O$	—	—	·04	·11
CaO	3·71	8·62	8·08	5·91
MgO	1·37	3·56	7·10	22·78
BaO	—	—	·06	nt. fd.
K_2O	2·76	·88	·70	1·09
Na_2O	6·52	3·54	4·50	·60
S	·10	—	—	—
FeS_2	—	·05	·11	—
CO_2	—	·58	·79	—
P_2O_5	·20	·37	·56	·38
H_2O (at 105° C.)	·14	·35	·12	·56
H_2O (above 105° C.)	·31	3·31	2·56	6·30
	100·13	99·97	100·73	100·70

I. Gwavas Quarry, Newlyn, Cornwall (analysed by W. Pollard). "The Geology of the Land's End District": Mem. Geol. Surv., 1907, p. 35.

II. Albite-diabase, Trusham Station Quarry, west side of Teign, Devon (analysed by E. G. Radley, E. 6808).

III. Proterobase, 200 yards north of viaduct, south-west of Cartuther, Cornwall (analysed by W. Pollard). "The Geology of the Country around Plymouth and Liskeard": Mem. Geol. Surv., 1907, p. 100.

IV. Hornblende picrite, Criffle Mill, Molenick, Cornwall (analysed by E. G. Radley). Ibid., p. 101.

The rocks that we have considered are of basic or ultra-basic composition, but acid and intermediate rocks also accompany the pillow-lavas. Of these we may distinguish the keratophyres (and albite-trachytes), quartz-keratophyres (and soda-felsites), and the soda-granites.

Keratophyres, etc.

The keratophyres are typically quartz-free. They consist of albite, chlorite, and iron-ores, and the structure varies from orthophyric to porphyritic; the phenocrysts are anorthoclase or albite. First described by Teall from the Southern Uplands of Scotland (25), and subsequently from Mevagissey in Cornwall (26), they have been found also in association with the pillow-lavas of Tayvallich (27), and the variolites of Fishguard (28). Quartz-keratophyres contain usually phenocrysts of corroded quartz and albite or anorthoclase, in a matrix that may be felsitic or microcrystalline. The soda-felsites are often strikingly perlitic. Quartz-keratophyres are common in Devon with the pillow-lavas there, and soda-felsites occur in the Southern Uplands of Scotland.

SODA-GRANITES.

The soda-granites are coarse-grained rocks, generally with phenocrysts of albite. The matrix is a holocrystalline mixture of quartz and albite. Ferromagnesian minerals are rare, but include biotite and pyroxene, the latter represented only by pseudomorphs. Rocks of this class occur at Porthallow in South Cornwall, where they are intrusive in the Ordovician pillow-lavas; and at Tayvallich in Argyllshire they penetrate the spilites that are interbedded with the limestones and schists of the Central Highland metamorphic series.

ANALYSES OF KERATOPHYRES, SODA-FELSITES, ETC.

	I.	II.	III.	IV.	V.
SiO_2	64·38	66·05	79·64	72·51	65·67
TiO_2	—	·49	·50	·31	·19
Al_2O_3	16·98	13·29	11·44	13·10	13·72
Fe_2O_3	4·04	3·22	·11	2·81	·50
FeO	—	5·07	·30	·90	1·17
MnO	—	—	·08	·20	·13
CaO	1·08	·50	·71	1·84	3·21
$(CoNi)O$	—	—	—	—	·02
BaO	—	—	—	—	·04
MgO	·28	1·36	·15	·20	1·52
Na_2O	7·57	6·67	6·40	6·76	6·26
K_2O	4·30	·87	·38	·33	1·68
Loss on ignition	1·64	1·88	·30	·35	·84
H_2O (at 105° C.)	—	·96	·16	·04	·28
P_2O_5	—	·09	·08	·06	·09
CO_2	—	—	·02	·76	4·86
FeS_2	—	—	—	—	·03
	100·27	100·45	100·27	100·17	100·21

I. Keratophyre, Hamilton Hill (analysed by J. J. H. Teall). "The Silurian Rocks of Scotland": Mem. Geol. Surv., 1899, pp. 88–9.

II. Keratophyre, Trevennen (analysed by W. Pollard). "The Geology of the Country around Mevagissey": Mem. Geol. Surv., 1907, p. 56.

III. Soda-rhyolite, west side of Skomer Island, top of cliff west of the spit (analysed by E. G. Radley, E. 7768).

IV. Soda-granite, Tayvallich, Argyllshire (analysed by E. G. Radley, S. 13221).

V. Soda-granite, north corner of Porthallow Cove, Cornwall (analysed by E. G. Radley, E. 6377).

We have, then, a long and varied suite of igneous rocks belonging to the spilite association. The commonest are always spilite and diabase; next in abundance are keratophyres and quartz-keratophyres; less frequently we find soda-granite, minverite, and picrite. They range from ultra-basic rocks like picrite to highly acid quartz-keratophyres, and their chief characteristic is the abundance of soda, even in the basic types. A close parallel can be drawn between them and the picrites (teschenites), dolerites and basalts, trachytes, and rhyolites of the Carboniferous rocks of Scotland (29). In both series felspar-free rocks occur (picrites and peridotites) and quartz-diabases, otherwise the spilite suite is always the richer in soda, and shows an additional characteristic, the almost universal and often complete albitization of the lime-soda felspars.

(*To be concluded in our next Number.*)